

Thermal Non-equilibrium Consistent with Widespread Cooling

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Abstract:

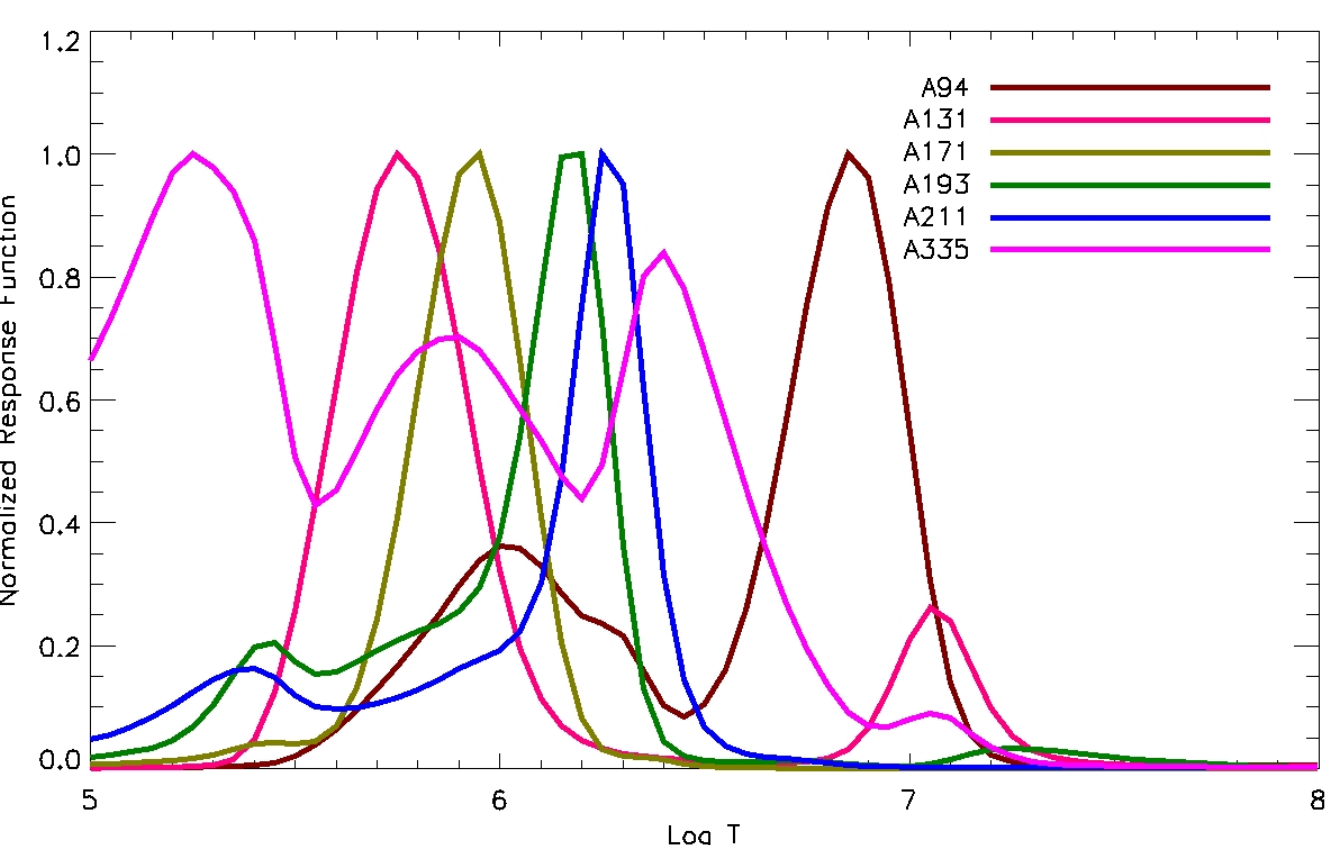
Time correlation analysis has been used to show widespread cooling in the solar corona; this cooling has been interpreted as a result of impulsive (nanoflare) heating. In this work, we investigate widespread cooling using a 3D model for a solar active region which has been heated with highly stratified heating. This type of heating drives thermal non-equilibrium solutions, meaning that though the heating is effectively steady, the density and temperature in the solution are not. We simulate the expected observations in narrowband EUV images and apply the time correlation analysis. We find that the results of this analysis are qualitatively similar to the observed data. We discuss additional diagnostics that may be applied to differentiate between these two heating scenarios.

The goal of this work:

- We will apply the analysis technique developed by Viall & Klimchuk (2012) to images generated from a 3D hydrodynamic simulation and demonstrate that steady, stratified (footpoint) heating is qualitatively consistent with the observations.
- We provide a quantitative comparison between episodic and footpoint heating and suggest a method of distinguishing the two models.

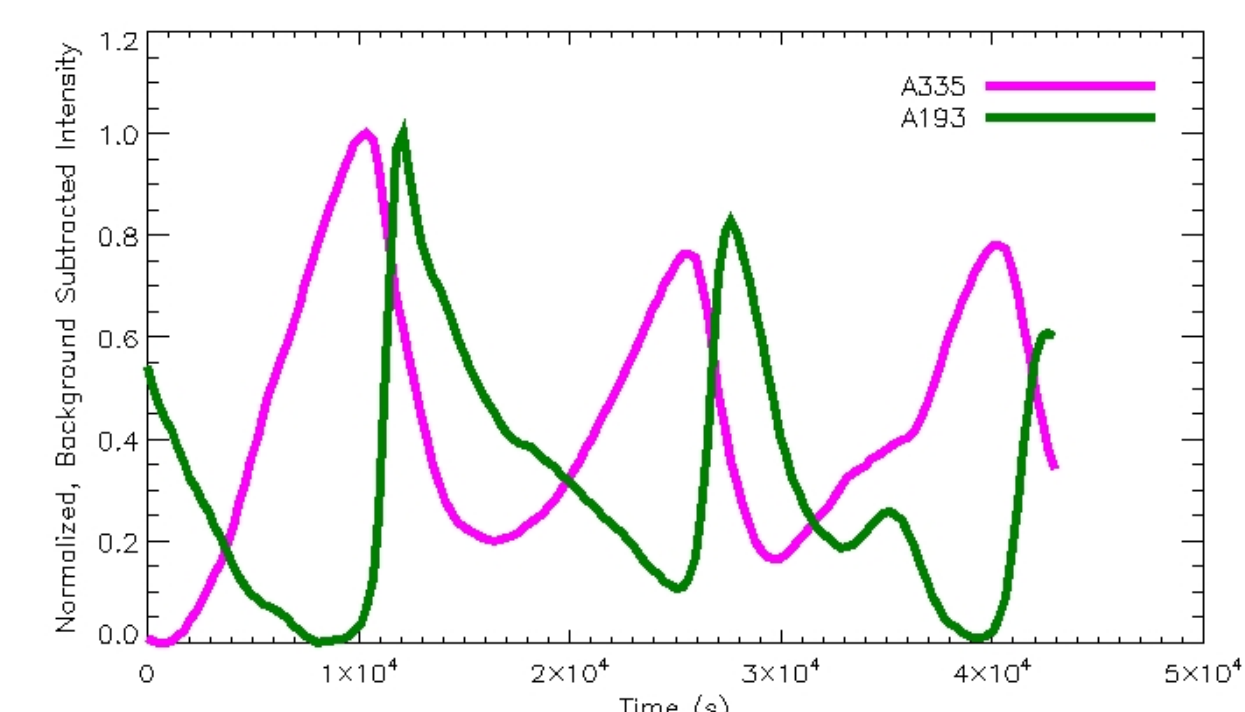
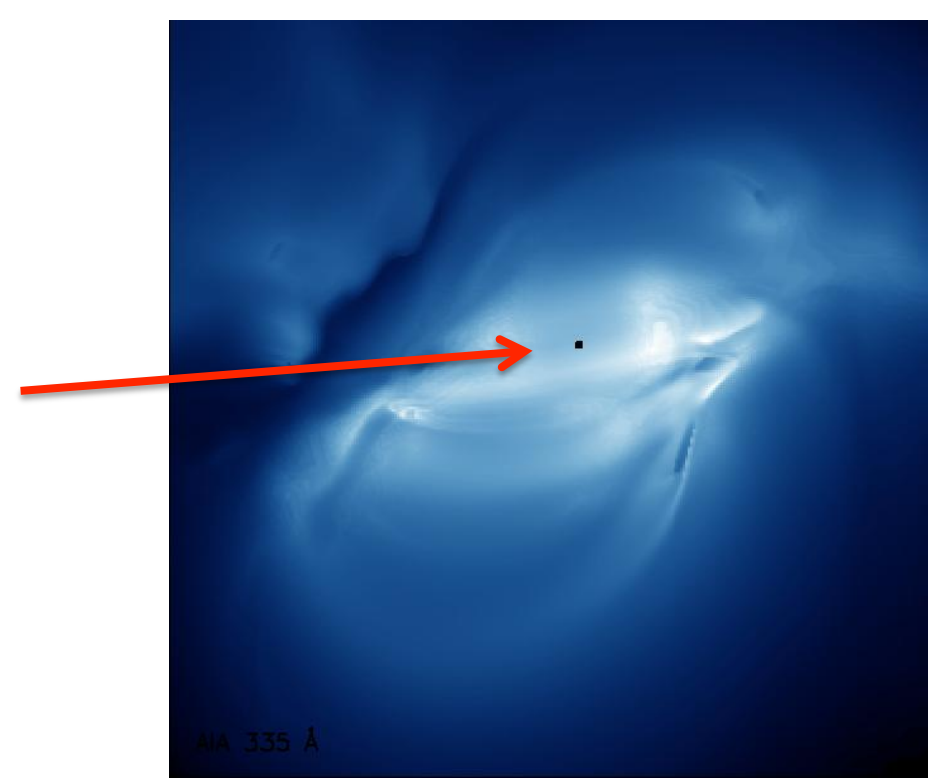
Analysis Technique (Viall & Klimchuk, 2012):

The narrowband EUV channels of AIA are sensitive to a wide range of temperatures. Structures evolving through these channels can provide information on the cooling characteristics of the structures.

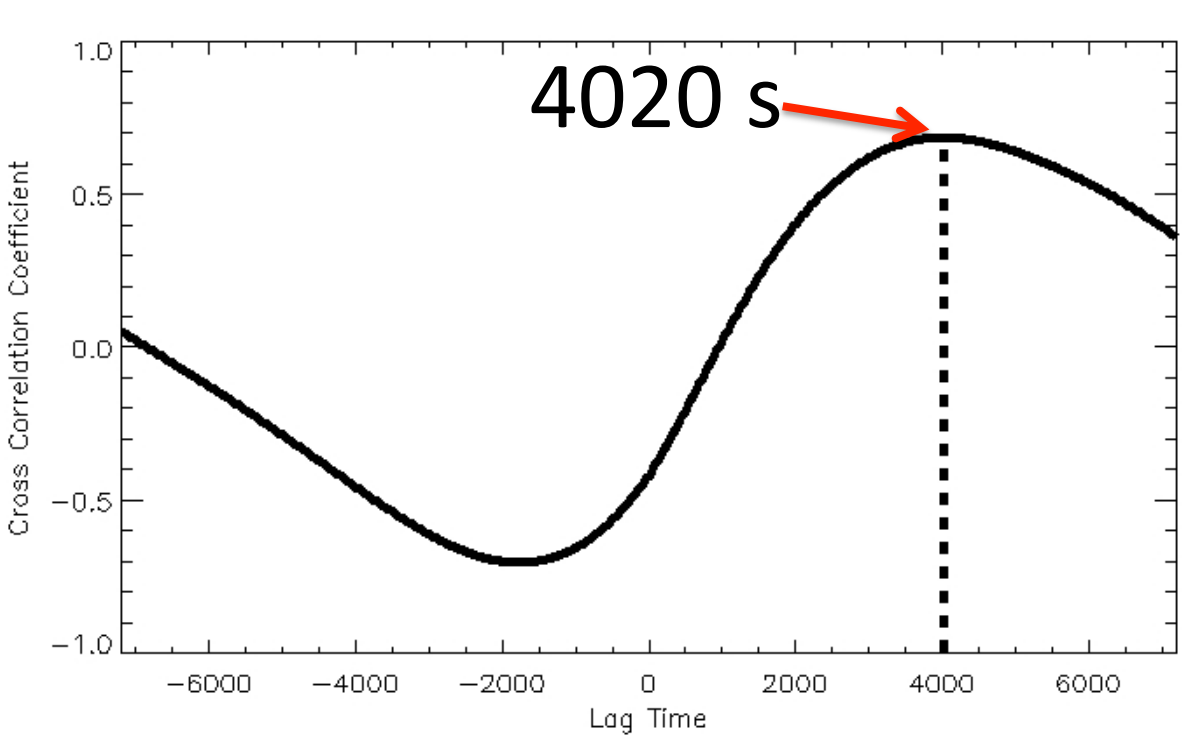


For the lightcurves at a single pixel in a pair of AIA channels, the IDL procedure C_CORRELATE.pro is used to compute cross correlation coefficient for different time lags. Both positive and negative time lags are allowed. In this example, we use 12 hours of data and allow the time lag to be +/- 2 hours.

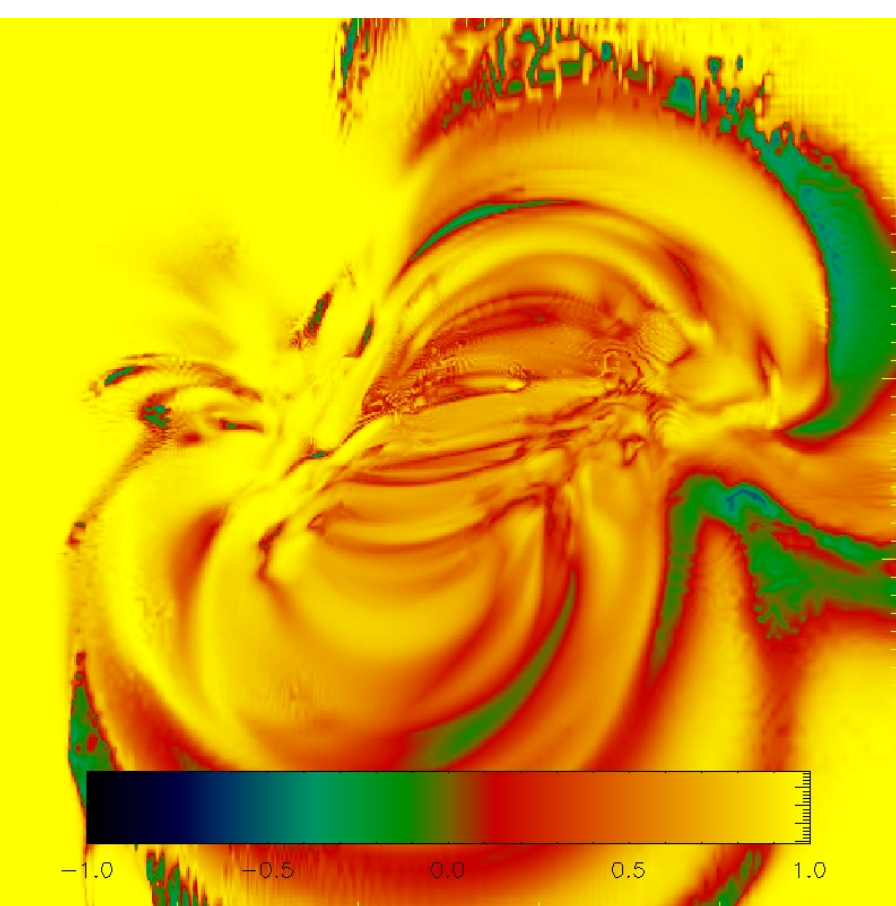
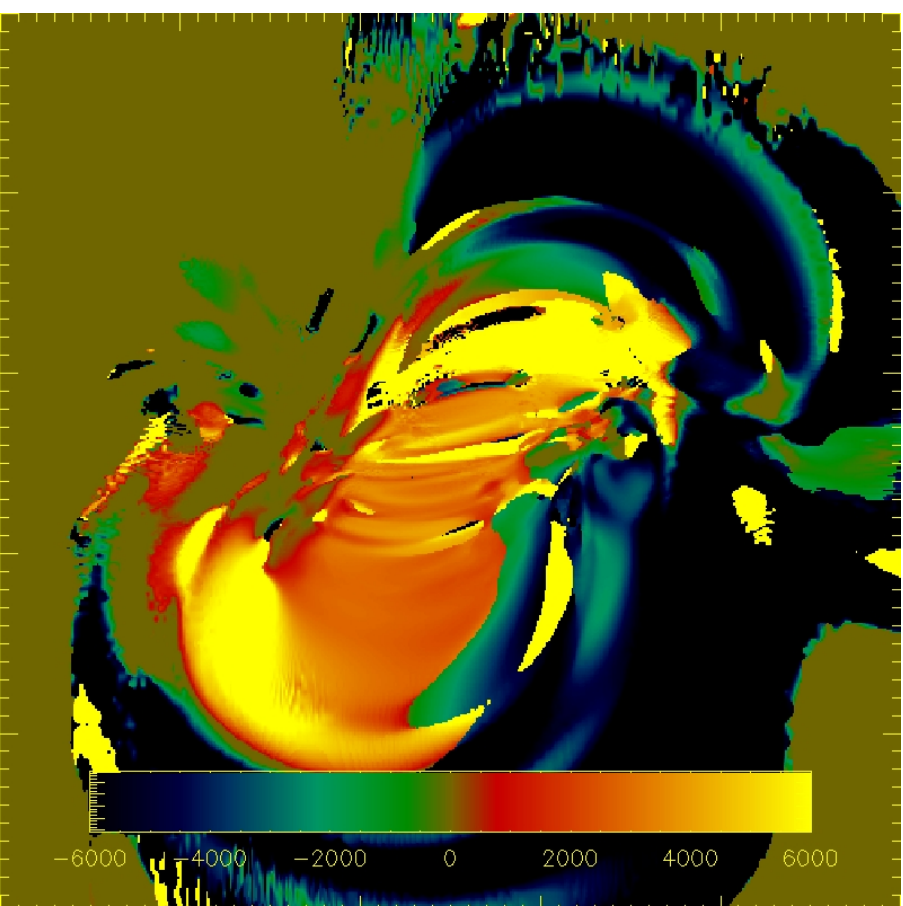
To demonstrate this technique, we use an example data point from the center of the active region.



The figure on the left shows the lightcurve of the 335 and 193 data at this point. In general, intensity enhancement in the 335 channel precedes intensity enhancement in the 193 channel.



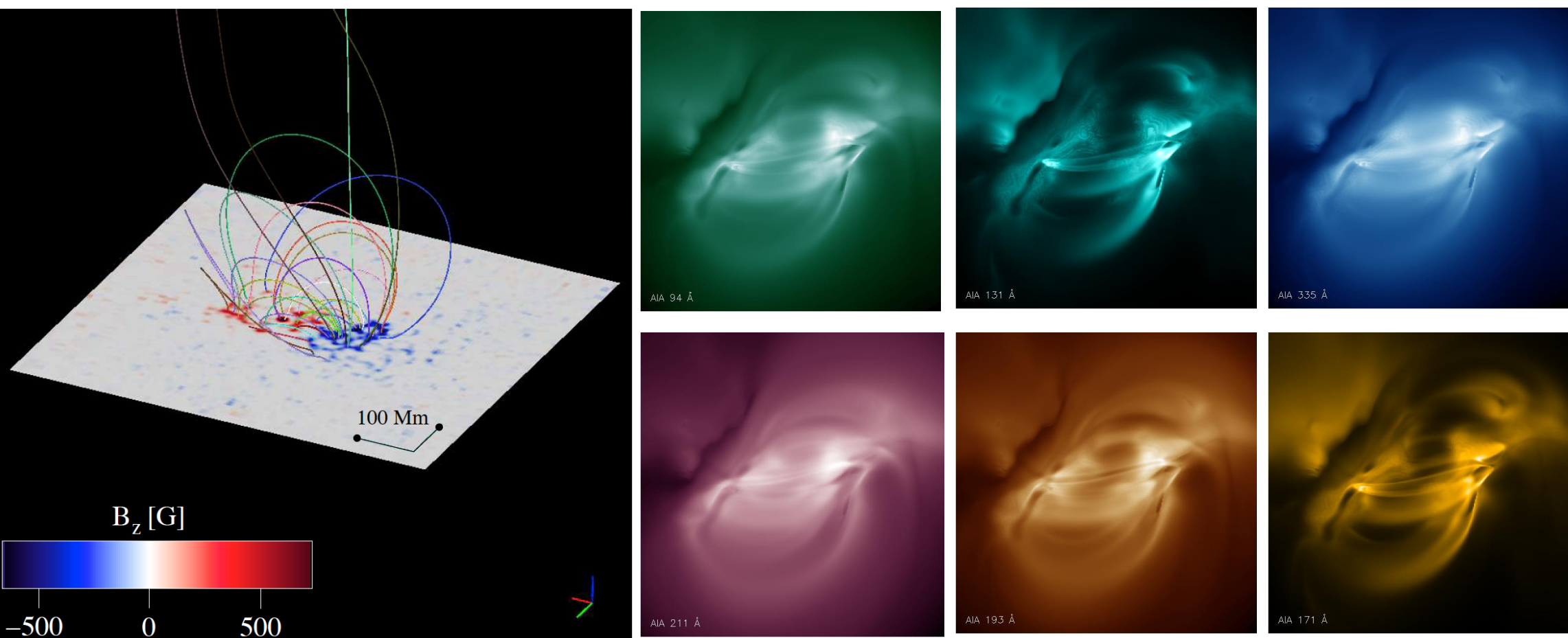
The two lightcurves are shifted by lag times and the cross correlation coefficient is calculated. The lag time where the cross correlation coefficient is the highest is then stored in the time lag map.



The time-lag map (left) and correlation coefficient map (right) are shown above for the 335-193 channels. Red and yellow colors in the time-lag map indicate cooling.

The 3D Hydrodynamic Simulations:

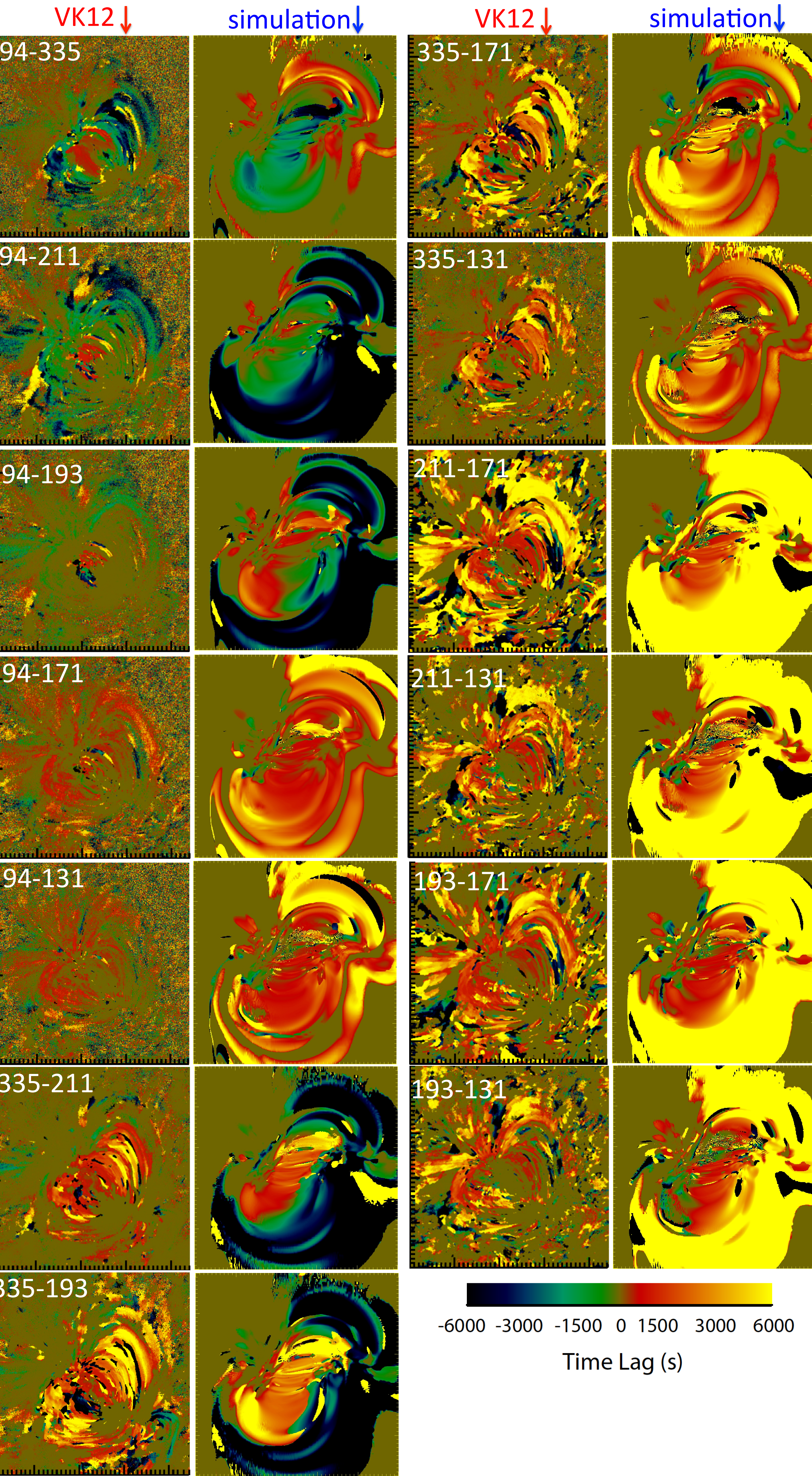
- We start with photospheric magnetic field measurements of AR 7986 from August 30, 1996 and use a 3D MHD code to relax the field to zero- β structure.
- Applying the heating rate $H = h_0 B^{7/4} n_e^{1/8} L^{-3/4}$ where B is the local field strength, n_e is the local electron density, and L is the loop length. This results in quasi-steady, highly-stratified heating.
- Using the resultant density and temperature, we calculate the emergent intensity expected in the AIA channels. The imaging cadence is 288.6 s for 20.8 hrs. We consider the last 12 hours.



Left : Photospheric field and some example field lines. Right: A set of AIA images from the end of the simulation.

Results:

Below we compare the time-lag maps from an active region observation (Viall & Klimchuk 2012) with those from our simulation.

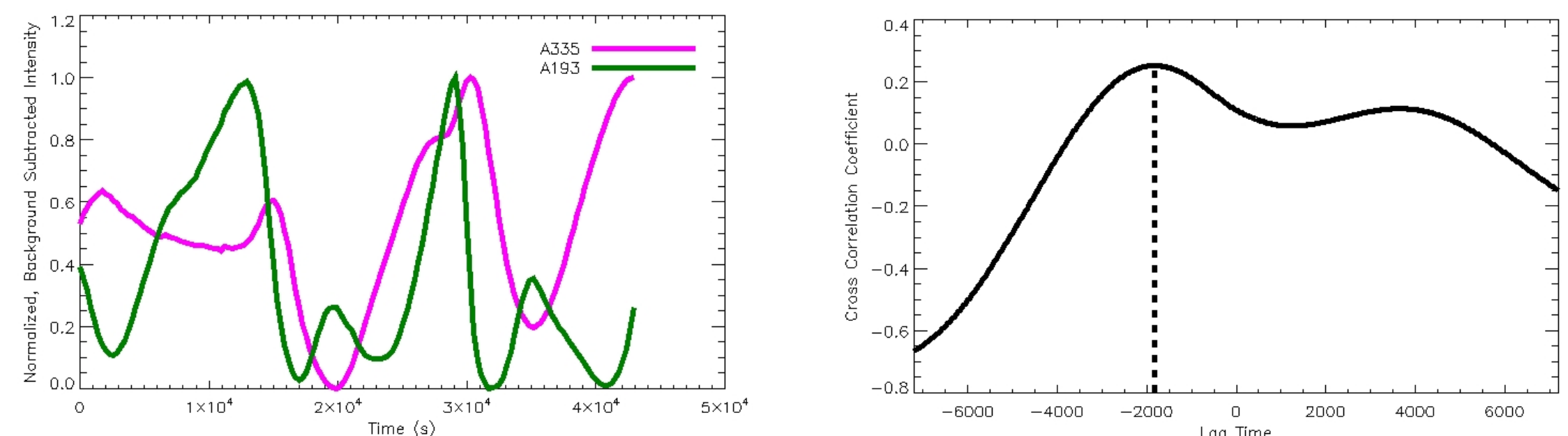


Results:

The time-lag maps calculated from the thermal non-equilibrium simulation are *qualitatively* consistent with the observations.

- The magnitude of the time lags are similar to the observed time lags.
- The time lags are smaller (red) in the core and increase away from the core. This is particularly clear in the 211 correlations.

Due to the cyclic nature of the solution to thermal non-equilibrium heating, this method can give confusing results when the highest correlation occurs with the previous cycle. Below is an example lightcurve where multiple structures along the line of sight and multiple cooling cycles present. This results in a negative time lag, though there is cooling structures along the line of sight.

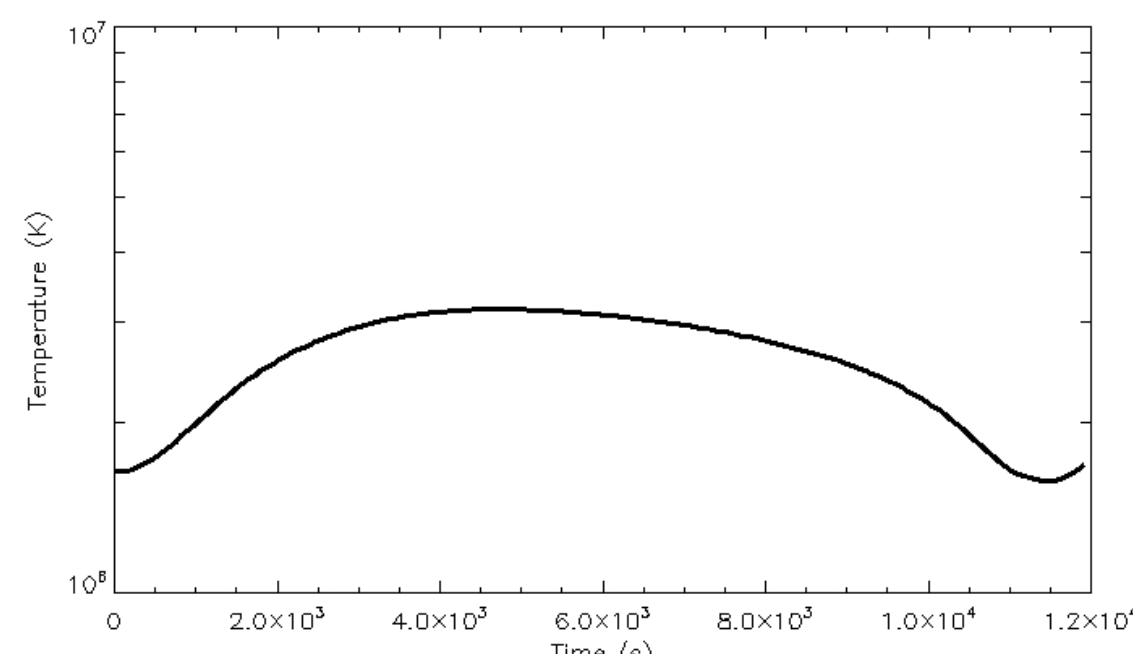
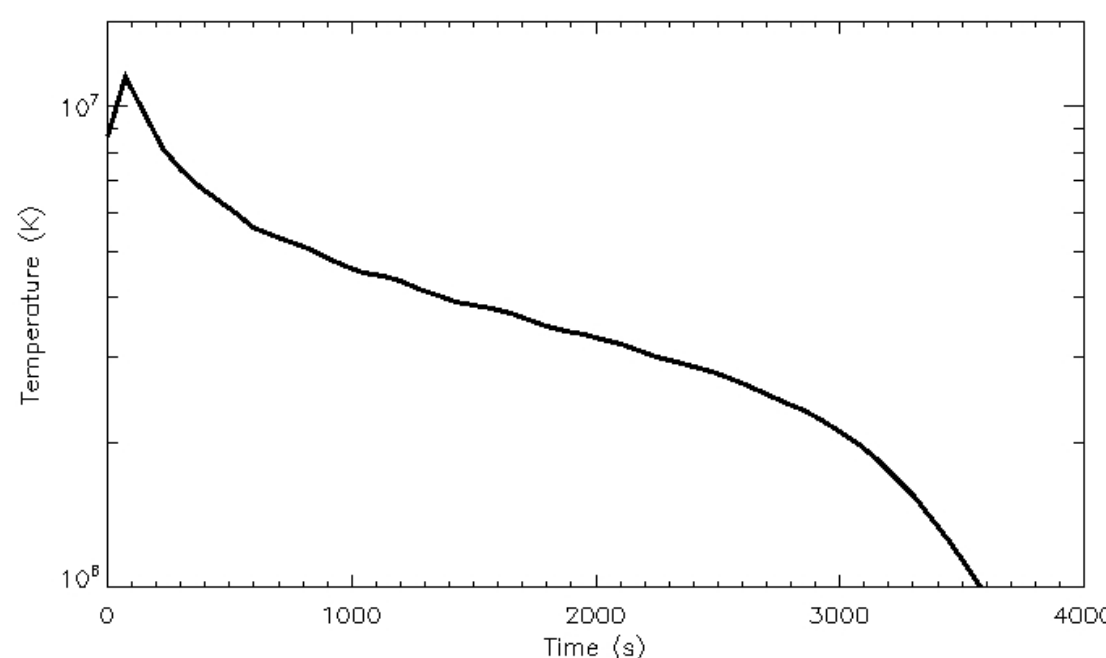


Differentiating footpoint and impulsive heating:

Given that both impulsive heating and footpoint heating produce qualitatively similar active regions, how can they be differentiated?

- To demonstrate, we use a 1D hydrodynamic code to compare the results of impulsive and footpoint heating.
- The loop we use the loop modeled in Section 7 of Mikic et al. (2013); the geometry and footpoint heating solution is described in that paper.
- Using the same geometry, we apply a triangular pulse of heating with a duration of 50 s. The heating is applied uniformly along the loop
- We choose the magnitude of the heating such that the AIA 335 channel has the same peak intensity as the footpoint heating solution.

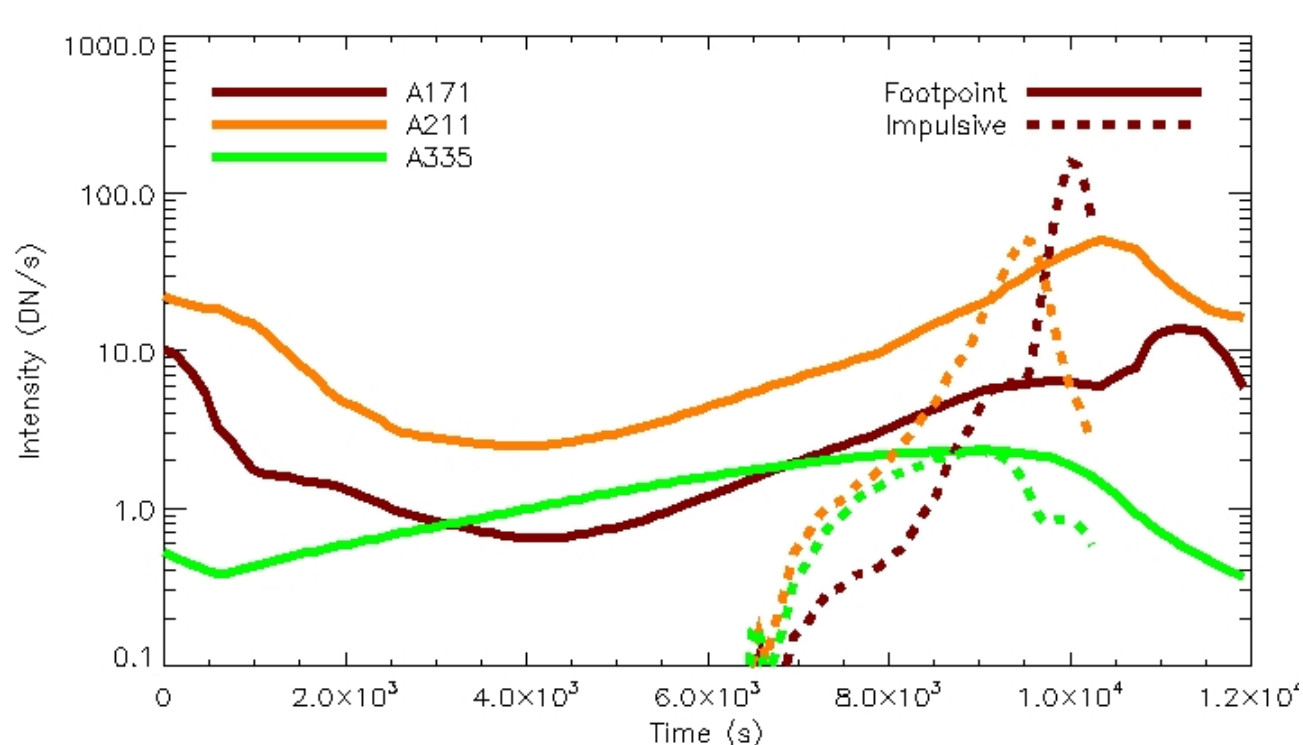
Footpoint Heating Solution: We select a single temperature cycle.



Impulsive Heating Solution: Note the time scale is different than the footpoint heating solution.

Comparison of the Lightcurves

We shift the impulsive heating solution so that both 335 lightcurves peak at the same time. The footpoint solution evolves slower than the impulsive solution and the relative intensities in cooler channels are different.



Conclusions:

- The time-lag maps for simulations using quasi-steady, footpoint heating are qualitatively similar to the observations.
- There are some locations where the time-lag might represent a cooling time, but if other structures are along the line of sight, the time lag could be misleading.
- A comparison of impulsive and footpoint heating solutions in 1D models suggest that footpoint heating should have longer time lags and smaller than expected intensities when compared to an impulsive solution. These observational parameters may be used to discriminate between the two models.